Is there Quark Matter in (Low-Mass) Pulsars?

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Abstract. The effect of the QCD phase transition is studied for the mass-radius relation of compact stars and for hot and dense matter at a given proton fraction used as input in core-collapse supernova simulations. The phase transitions to the 2SC and CFL color superconducting phases lead to stable hybrid star configurations with a pure quark matter core. In supernova explosions quark matter could be easily produced due to β-equilibrium, small proton fractions and nonvanishing temperatures. A low critical density for the phase transition to quark matter is compatible with present pulsar mass measurements.

The nuclear equation of state serves as a crucial input for several astrophysical systems. In supernovae simulations temperatures of $T = 20$ MeV and higher are reached with a baryon number density slightly above normal nuclear matter density at bounce [1]. In the subsequent evolution of the hot proto-neutron star the central density increases to several times normal nuclear matter density. In neutron star mergers the temperatures and densities reached are also in ranges where one expects the QCD phase transition from hadronic matter to a chirally restored phase. Hunting down strange quark matter in the heavens is coming of age and several signals have been suggested (see [2] for a review) as exotic mass-radius relations of compact stars, rapidly rotating pulsars due to a r-mode *stability* window, enhanced cooling of neutron stars, gamma-ray bursts by transition to strange quark matter, and gravitational wave signals from phase transitions in binary neutron star collisions, in the collapse of neutron star to a hybrid star or in the r-mode spin-down of hybrid stars. Interestingly, core-collapse supernovae have not been studied in that detail with regard to the QCD phase transition. One recent analysis in connection with quark stars has been done on the x-ray burster EXO 0748-676 stating that the mass and the radius should be in the range $M \geq 2.10 \pm 0.28 M_\odot$ and $R \geq 13.8 \pm 1.8$ km [3]. Contrary to the claims made by the author of [3], these constraints do not rule out quark stars or hybrid stars but rather soft equations of state [4]. In addition, a multiwavelength analysis arrives at the conclusion that the data is more consistent with a mass of $M = 1.35 M_\odot$ [5]. Also, the mass of the pulsar J0751+1807 has been corrected from $(2.1 \pm 0.2) M_\odot$ down to a value of $(1.26 \pm 0.14) M_\odot$

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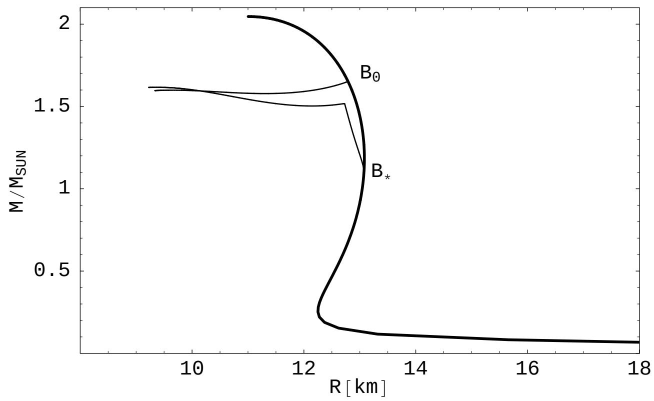

Figure 1. The mass-radius plot for hybrid stars showing the stable branches with a color-superconducting quark core (taken from [8]).

recently [6]. We point out that the masses of the supermassive pulsars reported in [7] are not real mass measurements as they rely on a statistical analysis of the orbital inclination angle of the binary pulsar system. We conclude that the present firm mass limit for neutron stars is still given by the Hulse-Taylor pulsar mass of $1.44M_\odot$.

There might be even more than one phase transition at high densities as there are several phases of color superconducting quark matter in β equilibrium, like the two-flavor color superconducting phase (2SC), the color-flavor locked phase (CFL) and its gapless versions, see [9, 10]. The generic impact on the global properties of compact stars is that a phase transition close to the maximum mass configuration will make the solutions with a quark core unstable [8]. A smaller critical energy density for the phase transition can generate a stable quark core. Within the Nambu–Jona-Lasinio model both the dynamical quark masses (quark condensates) and the color-superconducting gaps Δ are described. The 't Hooft term and a vector interaction term are taken into account. There are two free parameters left, one describing the diquark coupling G_D and another one the strength of the repulsive vector interaction G_V. In addition, the vacuum pressure is fixed either in vacuum (B_0) or at the chiral phase transition (B_*). In the latter case the switch from the hadronic phase (using a relativistic mean field approach) to the NJL quark description is exactly happening at the chiral phase transition. The difference in the two vacuum pressures is small but significantly moves the phase transition point to lower baryon densities. The hybrid star mass-radius diagram is depicted in Fig. 1. In the first case (B_0), the phase transition produces directly the CFL phase at high densities. The corresponding compact star is unstable first but is then stabilised for larger central densities. In the second case (B_*), two phase transitions are present, one from hadronic matter to the 2SC phase and the other one from the 2SC phase to the CFL phase. The two phase transitions produce two kinks in the mass-radius curve with two branches of stable solutions. The new stable solution constitutes the third family of compact stars. These phase transitions might have also implications for core-collapse supernova explosions by producing a secondary shock wave or by modifying the gravitational wave pattern from coalescing neutron stars.

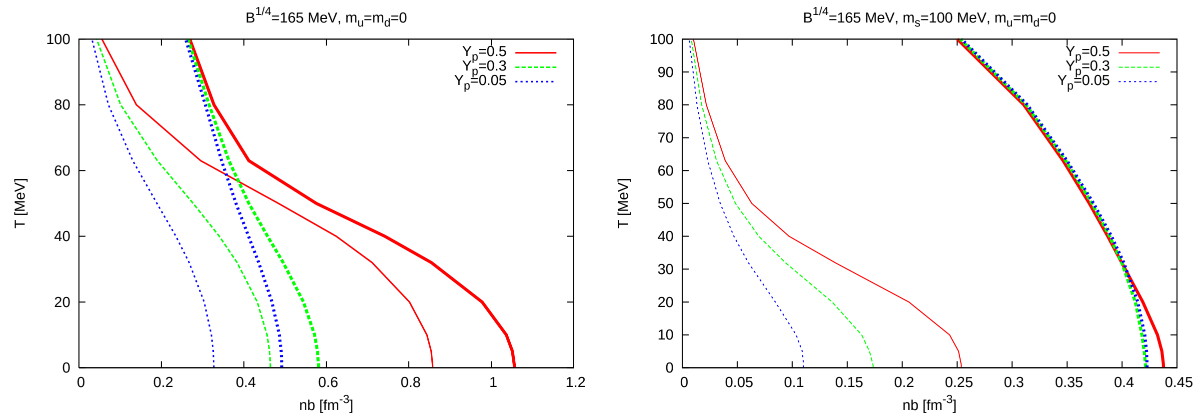

Figure 2. The phase transition lines to quark matter using the MIT bag constant for conditions relevant for heavy-ion collisions (left plot) and supernova explosions (right plot). Shown is the onset (thin lines) and the end of the mixed phase (thick lines).

In heavy-ion collisions the phase transition density to quark matter is different from supernova explosions. In the former there is no β-equilibrium established and consequently the pure hadronic and pure quark phases have vanishing net strangeness initially. Figure 2 shows the phase transition line between hadronic (the relativistic mean field model TM1) and a MIT bag equation of state at nonvanishing temperature and baryon density. Just up- and down-quarks are considered in the quark phase as there is no β-equilibrium. The critical density for the phase transition is quite large in particular for isospin-symmetric matter (proton fraction of $Y_p = 0.5$). Hence, the production of ud-quark matter is unfavoured for heavy-ion collisions at small temperatures and high proton fractions. The phase transition at large chemical potentials for ud-quark matter is located at higher values than the extracted freeze-out parameters from the statistical analysis of particle ratios at SIS and AGS energies. The phase transition to quark matter in astrophysical environments is dictated by β-equilibrium. The start of the mixed phase occurs already at quite low densities based on the enhanced stability of strange quark matter compared to ud-quark matter. The critical densities for isospin-asymmetric matter (low proton fraction Y_p) are even smaller due to the large asymmetry energy of nuclear matter. In comparison to cold neutron star matter, hot supernova environments favour the presence of quark matter as the phase transition line bends towards low chemical potentials for large temperatures. These three effects combined favour the production of quark matter already at quite early stages of the supernova evolution. We note that at supernova bounce typically $T \approx 20$ MeV and $Y_p \approx 0.3$ with densities slightly above saturation density $n_0 = 0.15$ fm^{-3}, so that quark matter could be present already at supernova bounce! The early onset of the quark matter phase corresponding to low values of the MIT bag constant was rejected in previous work with the argument that it produces a too small maximum mass for cold neutron stars [11]. This statement is not entirely correct, as small values of the bag constant result actually in a larger maximum mass *if* quark matter is the dominant phase of the compact star. We find that with the quark equation of state used here the maximum mass is well above

the 1.44 $M_\odot$ limit. The presence of quark matter drastically changes the mass-radius diagram. A stable solution appears with rather small radii for low-mass compact stars serving as a unique feature for the presence of exotic matter.

In summary, the phase transition to quark matter can have an enormous impact on the physics of compact stars and supernova explosions as the quark matter phase transition line is located at lower densities compared to the environment created in heavy-ion experiments. Hunting for supermassive neutron stars is, however, not a way to pin down the presence of quark matter in the heavens. Masses of neutron stars well above $2.3M_\odot$ are hard to achieve with *any* realistic modern nuclear equation of state. Constraints from heavy-ion data points towards a soft nuclear equation of state at moderate densities so that extremely large maximum masses are unfavoured [12]. A maximum mass of around $2M_\odot$ can be a compact star consisting just of normal nuclear matter or a hybrid star with a quark matter core [4]. If the maximum mass turns out to be about $1.5M_\odot$ (well below $2M_\odot$) exotic matter is involved which lowers the maximum mass, be it hyperons, kaon condensates or quarks. By measuring the radius of light pulsars, e.g. with masses of 1.2 $M_\odot$, the equation of state and the possible presence of exotic matter could be revealed with less ambiguities. If quark matter is present already at quite low densities it will lower drastically the radius of light compact stars. The conditions in core collapse supernovae are particularly favourable for the onset of the quark matter phase.

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References

[1] M. Liebendörfer, T. Fischer, C. Fröhlich, F.-K. Thielemann, and S. Whitehouse, J. Phys. G **35**, 014056 (2008), arXiv:0708.4296 [astro-ph].

[2] J. Schaffner-Bielich, PoS **(CPOD2007)**, 062 (2007), arXiv:0709.1043 [astro-ph].

[3] F. Özel, Nature **441**, 1115 (2006), astro-ph/0605106.

[4] M. Alford, D. Blaschke, A. Drago, T. Klähn, G. Pagliara, and J. Schaffner-Bielich, Nature **445**, E7 (2006), astro-ph/0606524.

[5] K. J. Pearson, R. Hynes, D. Steeghs, P. Jonker, C. Haswell, A. King, K. O'Brien, G. Nelemans, and M. Mendez, Astrophys. J. **648**, 1169 (2006), astro-ph/0605634.

[6] D. J. Nice, I. H. Stairs, and L. E. Kasian, AIP Conference Proceedings **983**, 453 (2008).

[7] P. C. C. Freire, S. M. Ransom, S. Begin, I. H. Stairs, J. W. T. Hessels, L. H. Frey, and F. Camilo, arXiv:0711.0925 [astro-ph] (2007).

[8] G. Pagliara and J. Schaffner-Bielich, Phys. Rev. D **77**, 063004 (2008), arXiv:0711.1119 [astro-ph].

[9] S. B. Rüster, V. Werth, M. Buballa, I. A. Shovkovy, and D. H. Rischke, Phys. Rev. D **72**, 034004 (2005), hep-ph/0503184.

[10] F. Sandin and D. Blaschke, Phys. Rev. D **75**, 125013 (2007), astro-ph/0701772.

[11] J. A. Pons, A. W. Steiner, M. Prakash, and J. M. Lattimer, Phys. Rev. Lett. **86**, 5223 (2001), astro-ph/0102015.

[12] I. Sagert, M. Wietoska, J. Schaffner-Bielich, and C. Sturm, J. Phys. G **35**, 014053 (2008), arXiv:0708.2810 [astro-ph].